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Author(s)	YAMAGATA, Kotaro
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RECENT GRAIN-SIZE COARSENING OF FLOODPLAIN DEPOSITS AND FOREST DECLINE ALONG THE KUISEB RIVER, NAMIB DESERT, NAMIBIA

Kotaro YAMAGATA

Division of Social Studies, Joetsu University of Education

ABSTRACT We investigated the flood plain deposits of the middle reach of the Kuiseb River in order to reveal the recent fluvial environment changes and forest decline. For the conservation of watershed environments, it is important to examine the relationship between environmental and hydrological changes. Fluvial deposits are useful for this as they record the past environmental changes in a catchment. Grain size coarsening was seen in the upper flood plain deposits in many places. The cause of the deposit coarsening was considered to be a relative increase in the supply of coarse material. The frequency of floods seems to have been decreased by the construction of many dams in the upper stream area, but sand dunes continue to advance on the river bed, increasing the relative supply rate of coarse material (dune sand). Notable forest declines were observed at the places where marked deposition of coarse sand had occurred, as such coarse deposits cannot retain water and are desiccated rapidly. The subsequent severe dry conditions at the roots induce tree death.

Key Words: Namib Desert; Kuiseb River; Riparian forest decline; Grain size coarsening; Flood plain deposit; Dam construction.

INTRODUCTION

The desertification of arid and semiarid lands is a serious global environmental problem (Arnalds, 2000). Global climate change and human activities are generally cited as major factors causing desertification (Darkoh, 1998). However, in many cases, local environmental conditions also play an important role in desertification. Thus, to understand the mechanisms of desertification and the desertification phenomenon in each region, the interactions among local environmental factors must be clarified.

Ephemeral rivers often occur in arid and semiarid areas, where they are important for the vegetation and local ecosystems that they support. However, the growth of human populations in arid environments has led to greater pressure on ephemeral rivers globally. The riparian zones of ephemeral rivers, in particular, are important elements in catchment ecosystems because these zones form the interface between terrestrial and aquatic ecosystems (Naiman et al., 1988; Gregory et al., 1991; Décamps, 1996).

Many studies have examined the role of fluvial processes in shaping sedimentological features along dryland rivers (Picard & High, 1973; Baker et al., 1988; Graf, 1988; Warner, 1988), but less attention has been given to the influence of these processes on soil properties of significance to riparian biota

(Jacobson et al., 2000). Studies to date have shown that moisture and nutrient availability, as well as soil salinity, are key factors influencing primary production in dryland riparian ecosystems (Jolly et al., 1993; Busch & Smith, 1995). The hydrological conditions of rivers fluctuate in response to changes in natural and artificial environments in the catchment area. Such changes in hydrological conditions can induce the erosion, deposition, and changes in the grain size of deposits. Furthermore, changes in the fluvial environment can affect vegetation along the river (Jacobson et al., 2000).

Ito (2005), Yamagata et al. (2004), and Mizuno & Yamagata (2005) reported the decline of riparian forest and Nara (*Acanthosicyos horridus*) vegetation along the Kuiseb River. The deforestation of riparian areas not only reduces wildlife habitat but also directly affects the stream and surrounding ecosystem by decreasing the water and habitat quality (Sweeney et al., 2004).

If the case of the Kuiseb River, human-induced hydrological change was inferred to be the cause of riparian forest decline. To conserve watershed environments, it is important to interpret the relationship between environmental change and changes in hydrological conditions. Fluvial deposits are a useful tool for such interpretations because they record the past environmental changes of the catchment. We investigated the floodplain deposits of the middle reaches of the Kuiseb River to examine recent changes in the fluvial environment and forest decline.

Several studies have investigated the influence of fluvial processes on ecologically relevant soil properties at a site within the Kuiseb River floodplain and have identified flood inputs as the key factor regulating organic matter and nutrient accumulation within the floodplain (Scholz, 1972; Abrams et al., 1997; Jacobson et al., 2000). These studies focused on the influence of soil chemical properties, however, the physical properties of soils also have large effects on the riparian ecosystem. Therefore, we investigated the relationship between recent changes in the grain size of floodplain deposits and riparian forest decline.

STUDY AREA

The Kuiseb River is one of the major rivers crossing the Namib Desert in west-central Namibia (Fig. 1). The river arises in the interior highland (Khomas Hochland) and drains a catchment of approximately 16,200km² as it meanders for 440km through the Namib Desert before reaching the Atlantic Ocean south of Walvis Bay (Fig. 2; Stengel, 1964). A strong climatic gradient occurs across the catchment. The mean annual rainfall exceeds 300mm in the headwater area on the inland plateau at elevations of 1,500 to 2,000m. Rainfall declines westward, becoming nearly zero at the coast (Jacobson et al., 2000).

The Kuiseb River is an ephemeral river that only flows after sufficient rain. The water discharge occurs as a flood. Because such temporal floods wash out the dune sand that advances to the north, the Kuiseb River marks the border

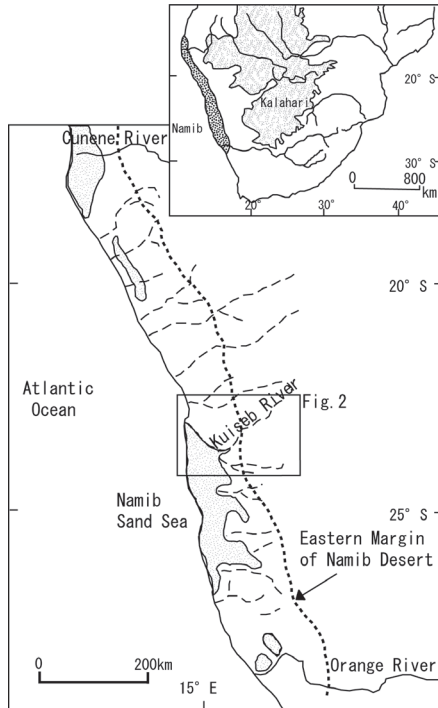


Fig. 1. The Namib Desert, showing major drainages, dune areas (dotted area), and location of study area (quadrangle area). Shaded area of Kalahari in the inserted map shows the distribution of the Kalahari Sand (adapted from Thomas & Shaw, 1991).

and revealed that these terraces were formed in response to climate changes since the last glacial age. The area is situated at the mouth of a canyon, so the fluvial terraces and floodplain are well developed. Under these geomorphic conditions, erosion and deposition should be strongly affected fluctuations in the hydrological conditions. Furthermore, the peak discharge rate of floods increases from the upper stream to the middle reaches around Gobabeb; discharge then decreases toward the lower reaches as it seeps underground. Therefore, floods have the largest influence in the middle reaches of the Kuiseb River.

TOPOGRAPHY AND SEDIMENT STRATIGRAPHY OF THE FLOODPLAIN

The fluvial terraces that occur along the middle reaches of the Kuiseb River around Gobabeb can be classified into four stages: upper (H); middle 1 (M1); middle 2 (M2); and, lower (L) (Fig. 3; Yamagata & Mizuno, 2005). Dead tree matter buried by dune sand on the L surface dates to 300 ± 60 years BP and 550 ± 50 years BP (conventional ^{14}C age; Mizuno & Yamagata, 2005). The calcareous crusts on the M1 surface date to $5,300 \pm 60$ years BP and $6,450 \pm$

between the sand desert to the south and rock desert to the north (Fig. 2).

The floods recharge the underflow water of the Kuiseb River. This underflow water supports a narrow riparian forest that plays an important role as a linear oasis in the desert ecosystem (Kok & Nel, 1996). The main woody species along the Kuiseb River are *Faidherbia albida*, *Acacia erioloba*, *Euclea pseudebenus*, and *Tamarix usneoides*. Of these species, *F. albida* and *A. erioloba* are of great economic and ecological importance, providing food for the livestock of local farmers and wild animals, as well as building materials, medicinal products, and shade (Seely & Griffin, 1986).

We conducted our study in the area around Gobabeb, situated in the middle reaches of the Kuiseb River, located approximately 60km inland from the coast of the Atlantic Ocean. Yamagata & Mizuno (2005) investigated the fluvial terraces that occur along this part of the Kuiseb River

50 years BP, whereas those of the M2 surface date to $22,070 \pm 260$ years BP (conventional ^{14}C age; Yamagata & Mizuno, 2005). There is no evidence of the ages of the upper terrace, but the erosion conditions suggest that they are older than several hundred thousand years. The presence of calcrete suggests that the groundwater level was higher when the M1 and M2 surfaces were formed than it is at present. The middle and upper terraces are devoid of vegetation, but the lower terrace is partially covered by *A. erioloba*, *nara* (*Acanthosicyos horridus*), and *Salvadora persica* (Fig. 3).

The riverbed and floodplain are currently forming topography. The riverbed is the portion in which floods always flow during the rainy season and contains almost no vegetation. The riverbed is 50 to 80m wide around Gobabeb and has distributaries in some places. The surface of the riverbed undulates gently and is mainly covered by sandy sediments.

The floodplain is a flat surface with widths of 20 to 200m. It extends from the riverbed to low cliffs of 0.3 to 1m in height. Small-scale undulations such as paleo-channels and aerial sand dunes occur in the floodplain. Although the vegetation densities differ, the whole area of the floodplain is mostly covered by forest (Fig. 3). The main woody species on the floodplain are *Faidherbia albida*, *Acacia erioloba*, *Euclea pseudobenus*, and *Tamarix usneoides*.

We observed the floodplain deposits at soil pits and outcrops around Gobabeb. In typical soil profiles, most of the sediments are sandy and show

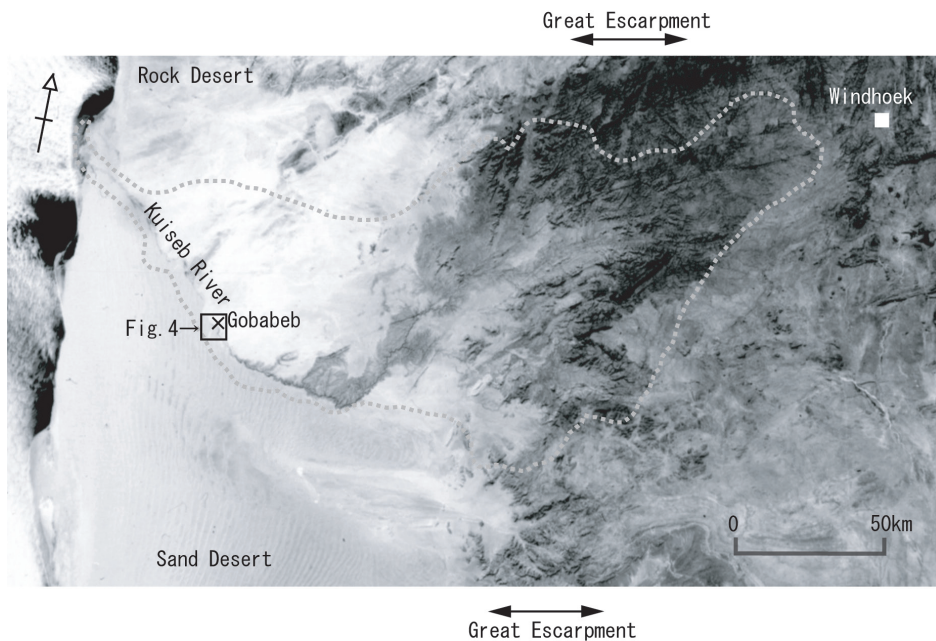


Fig. 2. CORONA satellite photograph of the Kuiseb River marking the boundary between sand desert and rock desert. (Imagery supplied by USGS; 1963/08/29) The dotted line is the boundary of the Kuiseb River basin.

alternation of coarse sand-rich layers and fine silt-rich layers (Fig. 4). This pattern suggests that the sediments were formed by many different floods. Some layers show thin lamination. Because the floodplain surface is washed by floods every year, the surface litter layer is very thin.

Grain-size coarsening occurs in the upper part of floodplain deposits at most places in the floodplain. The deposits in the lower part were massive silty sand, but those of the upper part were coarse sand deposits with parallel or slight cross-lamination. Such parallel lamination is thought to be formed during the downstream migration of low-relief ripples under shallow flows (McBride et al., 1975). Although the thickness of the coarse grain-size part changed in places, the boundary between the upper sandy part and lower silty part was consistently situated at almost 0.8m from the surface.

Figure 5 shows a sketch of the soil profile at Loc. 1 in Figure 4. The entire deposit is well layered. The grain size changes discontinuously. However, in general, the upper part is coarser and more sand-rich than the lower part. In particular, the profile clearly shows that the grain size becomes coarser 0.8m from surface; the grain size increases upward from this boundary to the surface.

Samples for grain-size analysis were taken every 0.2m in the profile. The grain size was analyzed using a sieve. Figure 5 shows the percentage of sand coarser than $63\mu\text{m}$ and the median diameter. The patterns of those two lines on the graph agree well. We confirmed that the grain size and sand content increase upward fluctuation. Remarkable coarsening at 0.8m from the surface was also confirmed.

We analyzed the mineral composition of samples from the upper coarse part and lower fine part under a microscope. There was a remarkable difference in mineral composition between these two parts. Quartz constituted a large portion

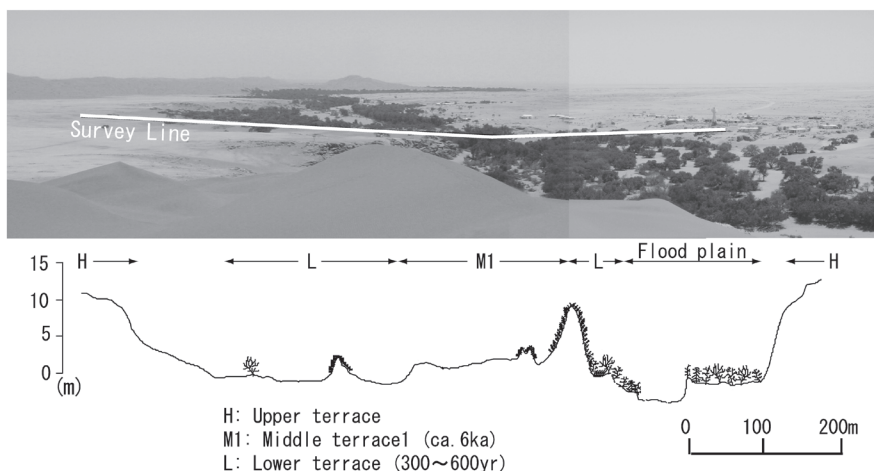


Fig. 3. Panorama view of the study area and topographic profile along the line on the photo showing the distribution of the vegetation.

of the upper coarser deposit, whereas a significant amount of mica occurred in the lower, finer deposit.

Because grain-size coarsening at the surface sediment was observed throughout the entire floodplain area around Gobabeb, such change is considered not to be caused by local conditions, but rather by changes in the hydrological conditions of the Kuiseb River. A plastic bag was found in the lowest part of the coarse sand part at Loc. 1 (Fig. 4). This suggests that the coarsening and rapid deposition of the floodplain deposits has occurred within the past several

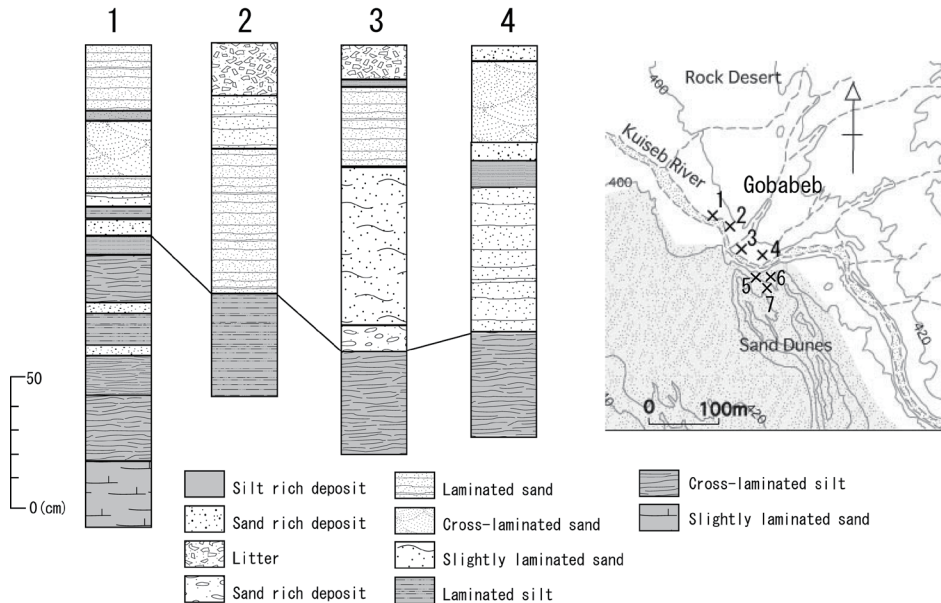


Fig. 4. Columnar sections of flood plain deposits.

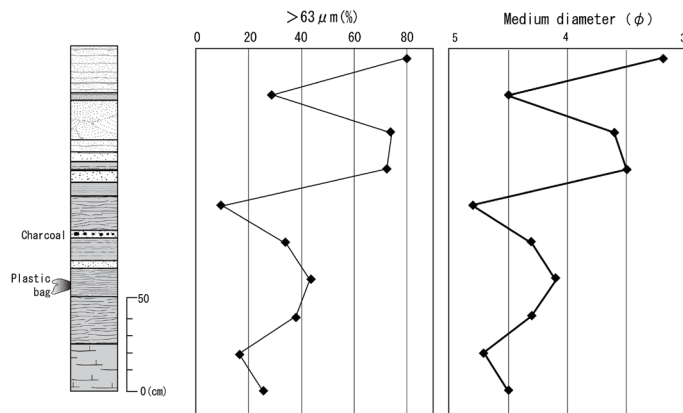


Fig. 5. Vertical Grain size variation of the flood plain deposits at Loc.1 in Fig. 4. Legends are same as in Fig. 4.

decades. This is also suggested by the occurrence of pieces of recently constructed structures such as fences in the flood deposits. Further, the radiocarbon age of a wood piece that was found just below the boundary between the lower silt and upper sand was calculated as 1960–1970 CE (Mizuno, 2005).

DISCUSSION

The survey indicated recent floodplain sediment coarsening in the middle reaches of the Kuiseb River. The cause of this deposit coarsening was considered to be an increase in flood flow or an increase in the supply of coarse material. Generally, in vegetated areas, rainwater permeates through the litter layer into the soil and then flows out gradually as groundwater. In contrast, in areas that are devoid of vegetation, heavy discharge occurs rapidly through surface flow, and erosion is very active. Therefore, increases in the flood discharge rate and in material supply generally occur together.

Figure 6 shows the distribution of land use around the Kuiseb River catchment. Most of the upper part of the catchment is grazing land of a large-scale landowner, whereas a national park occupies the downstream region. Because the downstream part is a very dry desert area with scarce vegetation, as well as a preservation district, signs of the progression of land degradation in recent years have not been found. Further, signs of a decline in the vegetation due to overgrazing and the accompanying erosion have not been observed in the grazing land in the upstream area.

In contrast, many dams have been constructed recently in the upstream area of the Kuiseb River, particularly since 1972, accompanying the increasing

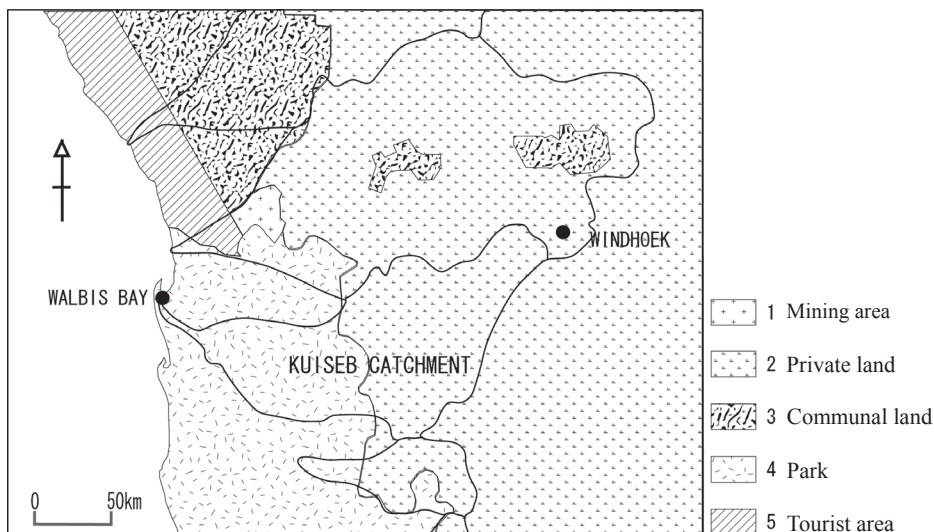


Fig. 6. Land use map of surrounding area of the Kuiseb River catchment (after Jacobson et al., 1995).

population and water demands of Windhoek city, which is contiguous with the Kuiseb River catchment (Fig. 7). The construction of so many dams is thought to have had a large influence on the hydrological environment of the catchment. The scale and peak discharge of floods have likely been decreased because floodwater is now stored by the dams. Additionally, much of the material transported by floodwater is likely trapped by the dams.

Figure 8 shows the annual length of the flooding period on the Kuiseb River at Gobabeb since 1962. These flood observation data indicate that the flood frequency decreased after 1976. In particular, very few floods occurred in the period from 1979 to 1984. Therefore, dam construction in the upper part of the catchment has decreased the flood discharge rate and material supply. Accordingly, the materials causing the coarsening of deposits in the middle reaches of the river have been supplied from areas other than the upper stream. That is,

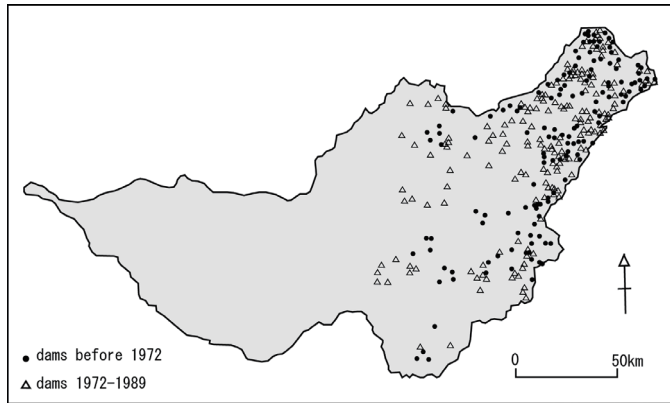


Fig. 7. Distribution of farm dams in the Kuiseb River catchment (after Jacobson et al., 1995).

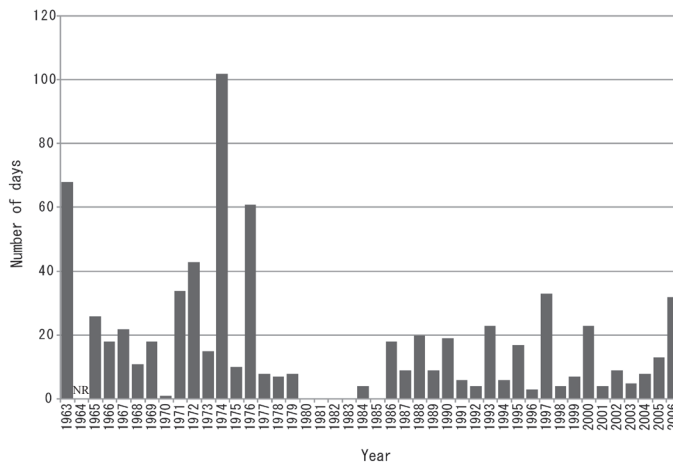


Fig. 8. Length of flood periods on the Kuiseb River at Gobabeb. 1963–1985: Seely et al., 1981; Ward and Brunn, 1985. 1985–2006: from data of the Gobabeb Training and Research Centre.

the cause of deposit coarsening has not been an increase in flood flows, but rather an increase in the supply of coarse materials.

The mineral composition of the upper coarse part and lower finer part differs remarkably. Whereas quartz dominates the upper part, a significant amount of mica composes the lower part. Mica schist is widely distributed over the upper region of the Kuiseb River (Mendelsohn et al., 2003), and it is thought that mica-dominant materials are supplied from this upper region. However, the quartz-dominant materials contributing to the coarsening of deposits must be derived from another area. A broad adjacent dune field extends to the south of the Kuiseb River, and the dune sand consists almost entirely of quartz and contains little mica.

Figure 9 compares the grain-size distribution of the upper coarse part and lower finer part of the floodplain deposits and dune sand. The peak of the grain size distribution of the upper part is larger than that of the lower part, and the upper part is better sorted than the lower part. These characteristics are similar to those of dune sand. Thus, the grain-size distribution and mineral composition suggest that the source of the coarse material is dune sand from the adjacent Namib Sand Sea.

The sand dunes advance toward the Kuiseb River floor at a rate of 1.20–1.45m/year, pushed by wind from the south (Mizuno, 2005). If floods occur frequently, the advanced portion is eroded little by little and transported downstream. However, the frequency of floods has decreased, and the sand dunes continue to advance toward the riverbed. Therefore, the relative supply rate of coarse material has increased. The percentage of material supplied from the sand dunes has probably also increased because upstream dams now trap finer materials from the upper stream. Further, materials that once would have been transported to the lower reaches of the river are probably deposited in the middle reaches around Gobabeb, which is situated at the outlet of Kuiseb Canyon, because lower flood flow has a lower transport capacity.

Notable forest declines were observed in places where remarkable coarse sand deposition occurred. Such coarse deposits may not be able to hold water

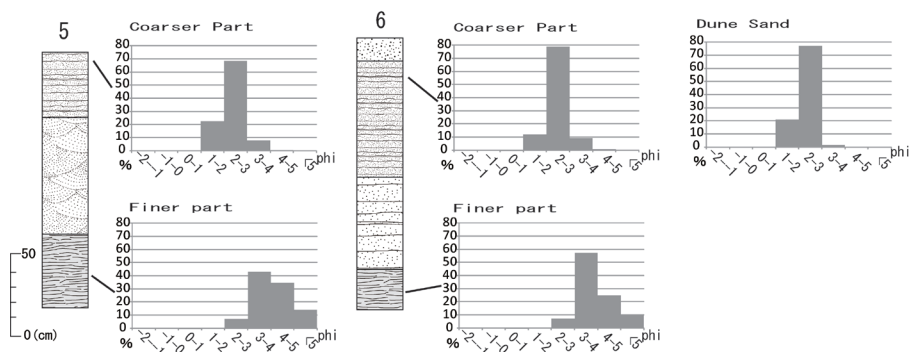


Fig. 9. Grain-size frequency distribution of flood plain deposits (Loc. 5 and Loc. 6) and sand dune deposit (Loc. 7). Legends are same as in Fig. 4.

well, leading to rapid desiccation. Severe dry conditions at the root level could lead to tree death. Soil profile observations confirmed that the lower silt-rich part was wetter than the sandy part. Furthermore, the silty deposits contain significant amounts of silicate sheets composed of mica minerals, which have high water retention; in contrast, the coarse deposits are composed mostly of quartz. We presume that a change to the latter mineral composition would induce a remarkable change in the soil water conditions.

Future research tasks are to investigate the extent of the effects of sand deposition and longitudinal change along the Kuiseb River. Meadow (2001) reported a recent increase in sand dunes and enlargement of the floodplain and delta area in the lower reaches of the Kuiseb River. Such phenomena could also be related to the increased supply of sandy material.

CONCLUSIONS

We investigated the floodplain deposits of the middle reaches of the Kuiseb River to determine the mechanisms of recent changes in the fluvial environment and forest decline. We have four main conclusions. First, grain-size coarsening of the upper part of the floodplain deposits was recognized at the middle reaches of the Kuiseb River. The radiocarbon age and buried materials in recent coarse deposits (e.g., plastic bags and fencing materials) suggest that the coarsening and rapid deposition of the floodplain deposits has occurred within the last several decades. Second, the grain-size distribution and mineral composition indicate that the source of the coarse material is dune sand from the adjacent Namib Sand Sea. Third, as the flood frequency has decreased due to the construction of dams upstream, less fine material has been transported from upstream, leading to an increase in the relative supply rate of coarse material. Fourth, severe drying may occur at the root level in such coarser floodplain deposits, inducing tree death.

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Author's Name and Address: Kotaro YAMAGATA, *Division of Social Studies, Joetsu University of Education, 1 Yamayashikimachi, Joetsu, Niigata 943-8512, JAPAN*

E-mail: kotaro@juen.ac.jp